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14. ABSTRACT
This report describes progress to date on establishing an integrated aperture, digital beam forming, and software receiver for UAV navigation in interference and jamming environment. Current progress has been made in the following areas: (1) Implemented both carrier and code phase tracking loop for performance evaluation of a minimum power beam forming algorithm and null steering algorithm (2) Developed a criterion for interference bandwidth classification (3) Implemented a multipath mitigation technique using joint space and polarization diversity.

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Integrated Reconfigurable Aperture, Digital Beam Forming, and Software GPS Receiver for UAV Navigation

AFOSR grant #FA9550-05-1-0035
Annual Progress Report
Principal Investigator: Y. T. Jade Morton

Department of Electrical and Computer Engineering
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1. Objectives

The main objective of this research project is to establish integrated hardware and software digital beam forming techniques for interference and jamming cancellation for the GPS receivers. The proposed project spans a three-year time period. Specific goals for the overall proposed project are:

- To develop robust and powerful adaptive anti-jamming techniques for a variety of jamming source types.
- To apply, test, and evaluate these algorithms using software GPS receivers using both simulated and real signals in a jamming environment.
- To establish an integrated test bed for evaluating future STAP processors, antenna development, array configurations, and receiver design.
- To obtain a through understanding of the impact of various hardware and STAP processor parameters on the performance of the integrated anti-jam receiver system.
- To discover and develop new methods that can be used effectively to improve the system performance, and to provide antenna designer feedback on desirable antenna capabilities and functions.
- To develop and provide effective solution for identifying jammer source location.

2. Status of Effort

The status of our effort can be best summarized through the general framework which we have established for testing, evaluating, and developing integrated aperture, receiver, and digital beam forming systems as shown in Figure 1.

The framework consists of four major components: signal generation, digital beam forming, software receiver, and performance evaluations. Subcomponents of the four major components are color-coded in the figure to show the status of progress of the subtasks. In the remaining part of this section, we will report the status of each of the component.

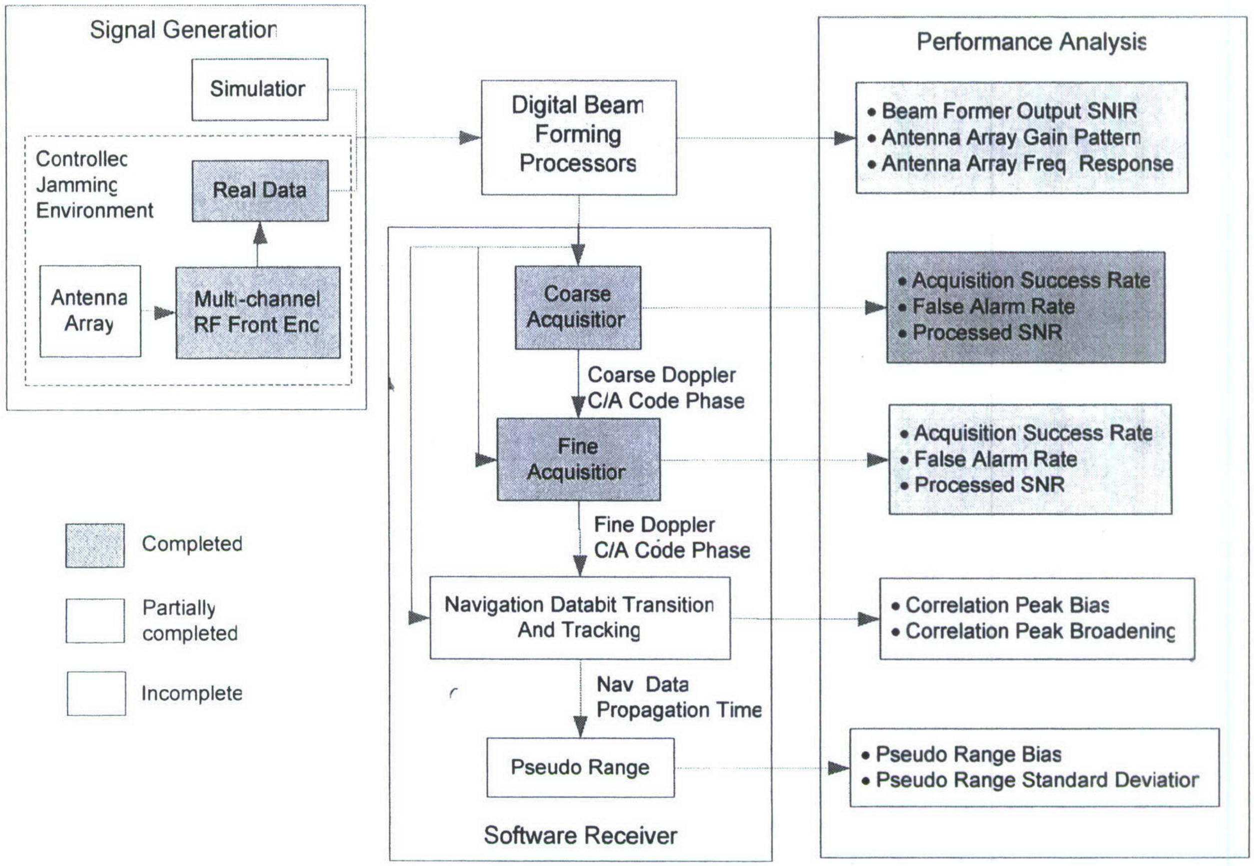


Fig.1. Framework for integrated aperture, software receiver, and digital beam forming research and evaluation system

2.1. Signal Generation.

GPS and jamming signals are generated through simulation and experiments under controlled jamming environment. Current status for the signal generation capability is summarized as the following:

- Simulation:
  - ✓ We completed simulated GPS input signals for a 4-element and a 9-element isotropic antenna array.
  - ✓ We are in the process of simulating additional jamming signals for the isotropic antenna array.
  - ✓ We are in the process of simulating GPS inputs signals and jamming signals for a single reconfigurable antenna element based on the simulated antenna characteristics provided by the Ohio State University.
- Real data:
  - ✓ We worked with real data collected in controlled jamming environment using a 4-element conventional antenna array and a 4-channel RF front end. A total of 8 GPS satellites are contained in the experimental setups. Three types of interference signals are used in the

experiments: FM chirp, BPSK, and broadband. A total of 33 sets of experimental have been used in the studies. The following jamming scenario have been studied: one FM chirp source, one BKSP source, one broadband source, two broadband sources, and three broadband sources. The studies using the FM chirp and BKSP interference sources have been presented in Morton et al. (2004). Figure 2 shows the experimental set up to obtain the real data. Figure 3 shows the satellite constellation used in the experiments. Figure 4 shows the RF front end schematics used in the data taking.

✓ We are in the process of planning additional experiments using the Ohio State University's reconfigurable experiments. Two types of experiments are being designed: (1) experiments using one antenna element to validate the receiver simulation performance, and (2) a 4-element antenna array using reconfigurable elements and 4-channel receiver front end to collect GPS and jamming signals in controlled jamming environment. We will carry out the first set of experiments as soon as we receive the antennas.

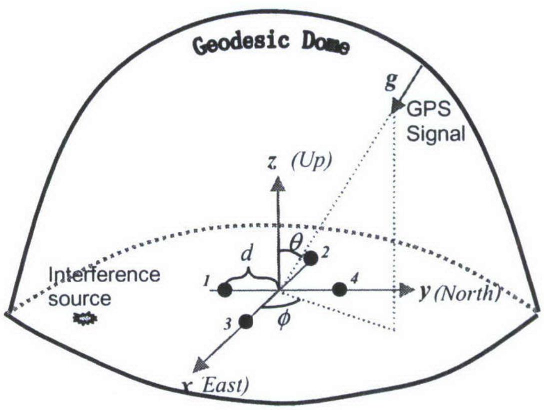


Fig. 2. Antenna elements layout and experimental setup.

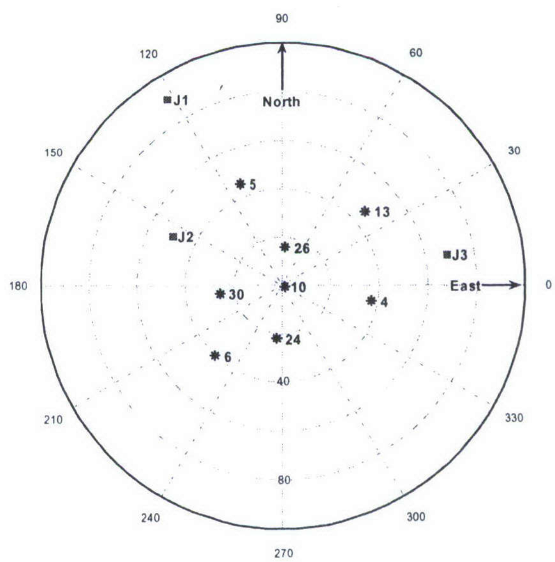


Fig. 3. Sky view of satellites and interference sources in the experimental setup

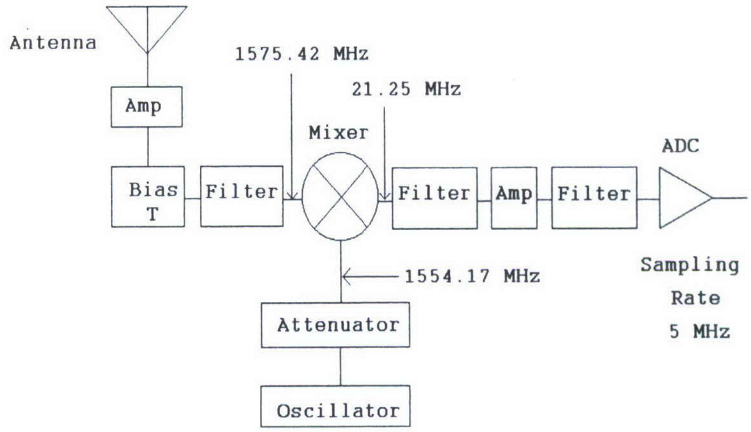


Fig. 4. Block diagram of a single channel GPS receiver RF/IF front end

2.2. Digital Beam Forming.

Three digital beam forming processors have been implemented and tested. Their performances have also been evaluated. These processors are:

- Spatial MOP with signal angle of arrival (AOA) constraint. This algorithm is based on the fact that GPS signals are far below noise level. By minimizing a cost function related to the total input power while maintaining gain along AOA of a known satellite, we can achieve the goal of suppressing the jammer contribution to the total input with minimum impact on the GPS signal (Zoltowski and Gecan, 1995]. This processor does not include any time domain processing. Figure 5 shows the general schematics of a spatial processor.
- Space-time MOP with signal AOA constraint. This processor differs from the spatial MOP by including tapped delay lines in the each input channel before combining the input data for the software receiver processing (Aimin et al, 2003). These tapped delay lines introduce a filter for the input data, leading to a space-time beam forming implementation. A number of configurations using different numbers of taps and different tap delays are implemented. These configurations performance are evaluated. Figure 6 shows the schematics of a space-time processor.
- SCORE. The SCORE method explores the unique characteristics of a class of signals that are *spectrally self-coherent*, ie, the correlation between a signal $s(t)$ and its frequency-shifted version for some time lag is non-zero (Sun and Aimin, to be published). Because of the periodic nature of GPS C/A code, an optimization function is defined that maximizes the self-coherence of the entire ensemble of GPS signals at the receiver input. The optimization solution generates a set of weight vectors that maximize gains along the directions of all satellite whose signals are among the total input while minimizing jammer inputs.

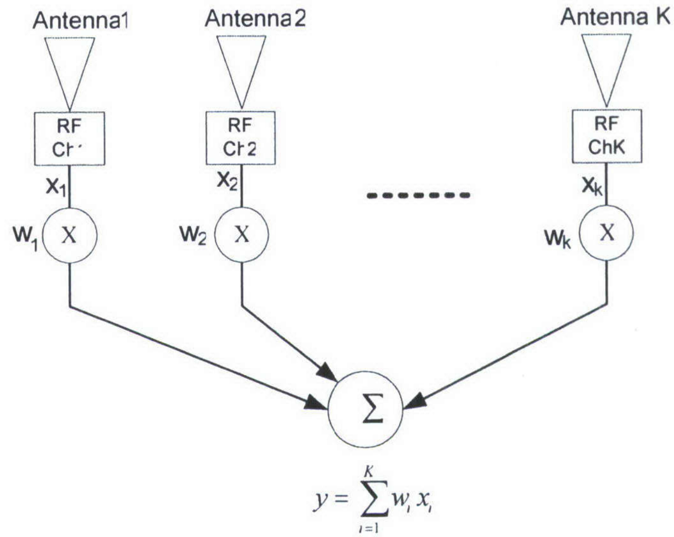


Fig. 5. Schematics of a K-element antenna array spatial adaptive processor

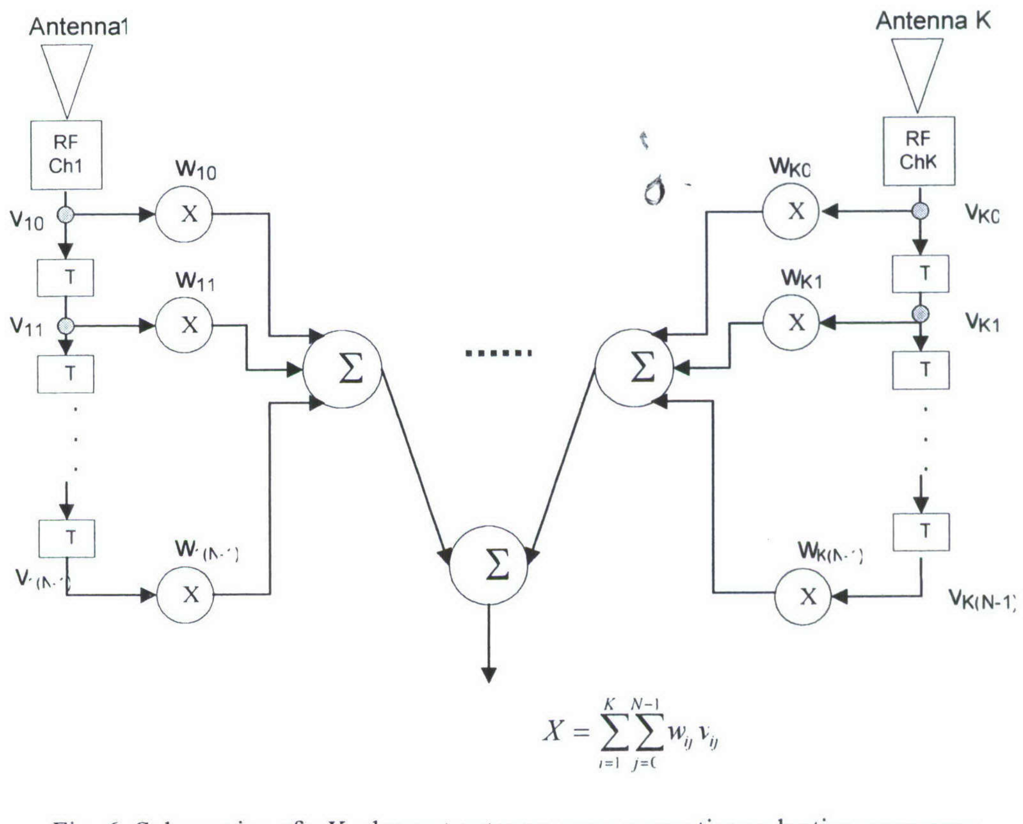


Fig. 6. Schematics of a K-element antenna array space-time adaptive processor

Two additional beam formers are in the process of being implemented. These processors are based on minimizing cost functions that are related to the ratio or difference between desired GPS signals and total interference and noise.

2.3. Software Receiver.

A software GPS receiver consists of signal processing algorithms that perform the following functions: coarse and fine acquisition of GPS signal's Doppler frequencies and C/A code phase, navigation data bit detection, tracking of GPS signal carrier and code, and receiver-satellite pseudorange calculations. In order to best utilize the beam former output, software GPS receiver acquisition algorithms specifically developed to work with weak GPs signals are implemented for the integrated system. The weak signal coarse acquisition algorithms combine both coherent and non-coherent integration techniques to work with relatively long input data streams (Tsui, 2004). Based on simulation and previous real data experimentation, the weak signal acquisition algorithms are capable of acquiring GPS signals with input carrier signal to noise ratio (C/N0) in the order of 24 dB-Hz, keeping in mind that nominal GPS signals input a carrier signal to noise ratio of around 48 dB-Hz. The coarse acquisition algorithm outputs Doppler frequencies with a resolution of 100 Hz. It also generates the C/A code phase.

Because the beam former output may contain weak GPS signals, a fine frequency resolution is necessary in order to determine navigation data bit transition and tracking the GPS signal carrier and code. The fine acquisition algorithm takes advantage of the course frequency knowledge and applies coherent integration techniques in the frequency domain. A fine frequency acquisition algorithm has been implemented and tested successfully using simulation and experimental data. Figure 7 shows the software GPS receiver block diagram of process and parameter flow for the coarse and fine acquisition. Fig. 8 shows the flow chart for the acquisition algorithm. Figure 9 shows the flow chart for the fine acquisition algorithm.

Navigation data bit transition and tracking algorithms will be implemented and tested in the next stage of research.

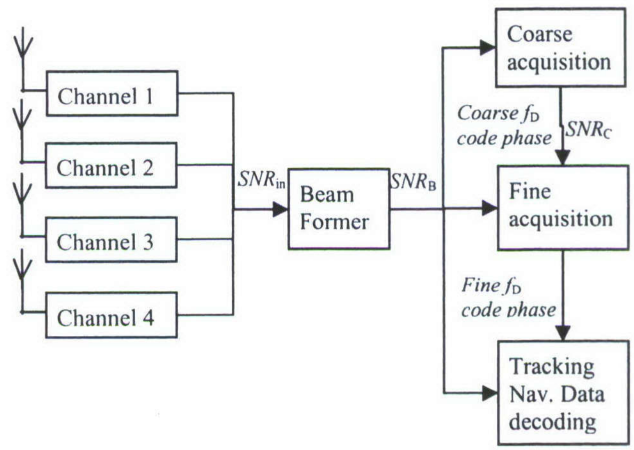


Fig. 7. Block diagram of process and parameter flow for coarse and fine acquisition.

2.4. Performance Evaluations.

Performance evaluations are carried out for the three beam formers described in Section 2.2. Antenna array gain patterns, coarse acquisition success rate and false alarm rate, fine acquisition success rate and false alarm rate, and beam former output signal to noise ratio are obtained and used to evaluate the beam former performance.

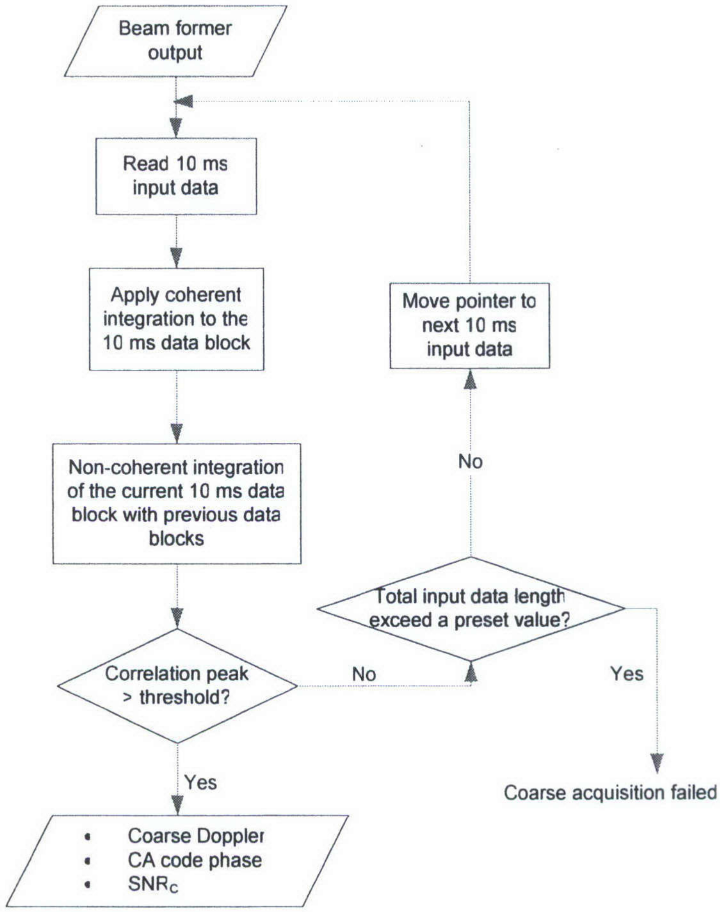


Fig. 8. Coarse acquisition flow chart.

2.4.1 Antenna array gain pattern.

A visualization method was developed to exam the gain pattern of the antenna array (Morton et al, 2004). The gain pattern is plotted in the same manner as the sky plot for astronomers. Line and colors are used to indicate the magnitude of the antenna array's gain. GPS satellites and jammer locations can also be displayed in the plot. The antenna array gain pattern provides a visual means to study the effectiveness of a beam former. Fig. 10 shows two example gain pattern plots for experimental data processing. Figure 10.a is obtained using the MOP method with only spatial processing. Satellite 30 AOA is the constraint for the beam former. The red square indicates the location of an active broadband Jammer #2. The gain pattern clearly indicates that the beam former successfully maintained strong gain along the direction of the satellite while placing a null at the jammer direction. Fig. 10.b is the gain pattern obtained using the SCORE method. Three active jammers (yellow squares) are present in this set of data. The beam former failed to provide enhanced gains along the satellites and suppress the inputs from the jammers. The antenna array gain pattern visualization technique has proven to be essential for the integrated system evaluations.

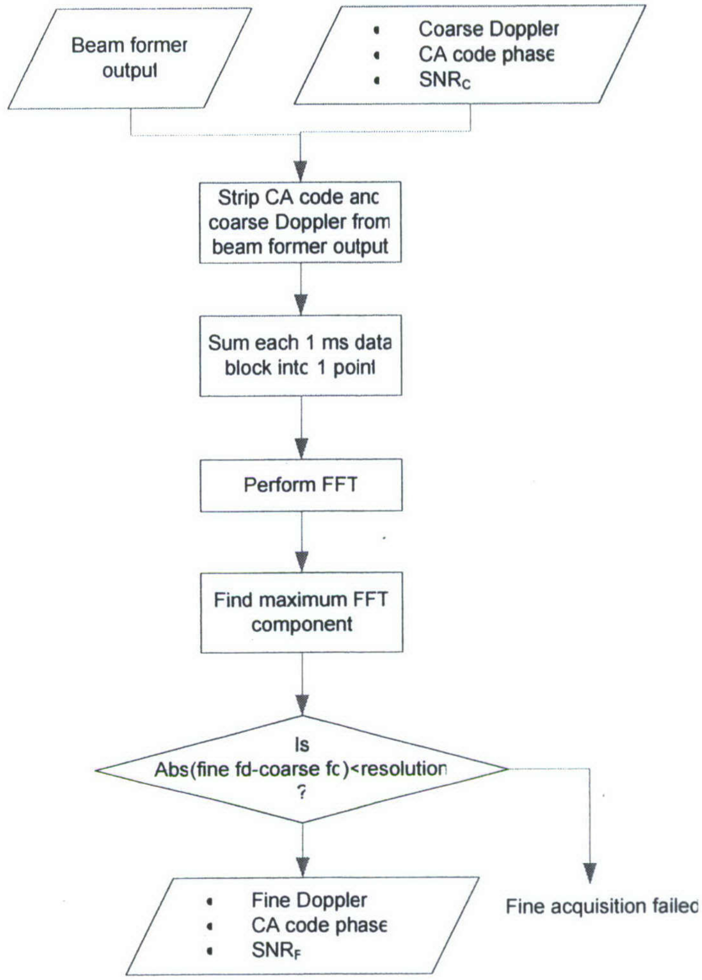
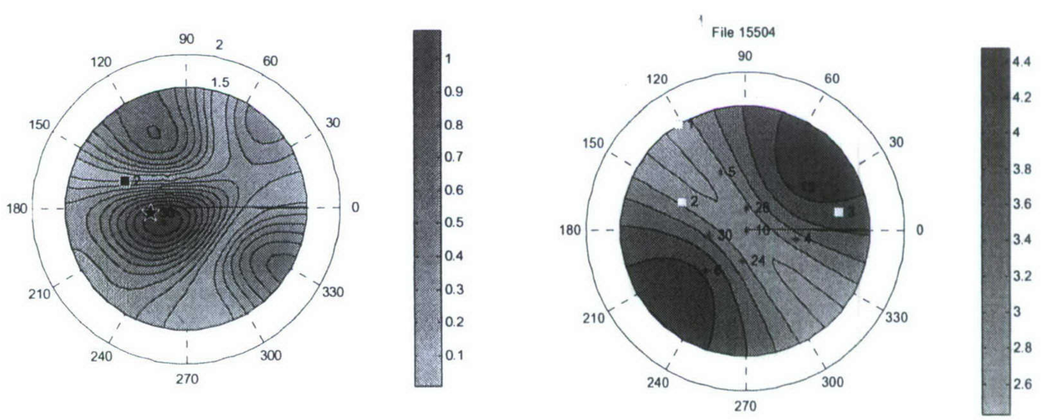


Fig. 9. Fine acquisition flow chart.



(a) (b)

Fig.10. Example antenna array gain patterns.

Additional visualization means are currently being developed to study the frequency response of the antenna array.

2.4.2 Coarse acquisition success rate and false alarm rate.

The first set of quantitative measures for the beam former and the software coarse acquisition algorithm are the acquisition success rate and false alarm rate. In order to separate the effects of the beam former and the software receiver coarse acquisition algorithm, we performed simulation studies of the coarse acquisition algorithm performance for single antenna case. Figure 11 shows the acquisition success rate for the coarse Doppler acquisition procedure depicted by the flow chart in Figure 9. Each data point in this plot is generated from over 500 simulation runs.

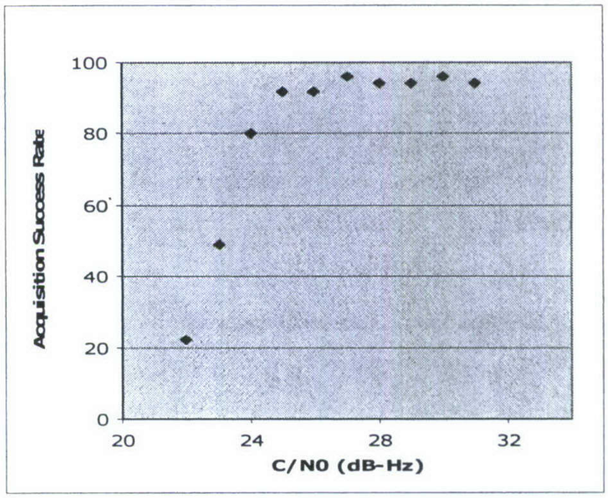


Fig.11. Coarse acquisition success rate as a function of GPS signal C/N0 (dB)

We also applied the same coarse acquisition algorithms to the output of three different beam formers. A total of 21 sets of experimental data were processed using the integrated receiver system. Each set contains 8 GPS signals. Therefore, a total of 168 acquisitions were performed. Figure 12 contains three plots that show the average numbers of satellites that can be successfully acquired through the coarse acquisition for the cases where one, two, and three broadband interference sources are present. The colored bars distinguish the type of beam formers used prior to the acquisition procedure. We can draw several conclusions from the plots:

(1) Both space-only and space-time beam former improves the acquisition success rate. The improvement is especially impressive when the interference source power is relatively high, and only one interference source is present.
(2) The space-time beam former performance is comparable the spatial-only beam former. There is no significant improvement in the number of satellite acquired using space-time beam former.

(3) Both beam former failed in three interference sources environment when all three interferences to GPS signal power ratios (ISR) are 40 dB. This is anticipated because we have reached the limit of the beam former's degree of freedom.

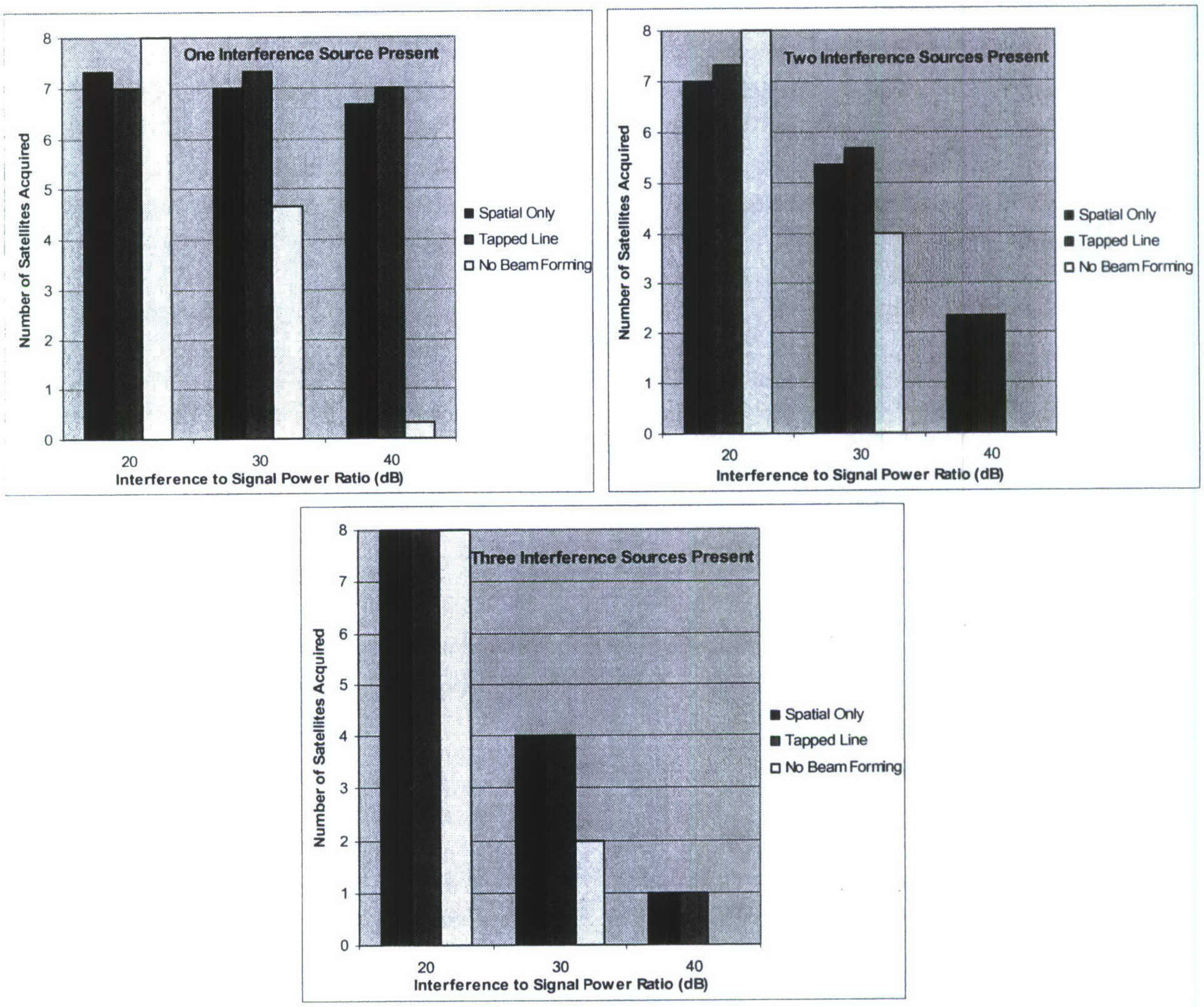


Fig. 12. Average number of successful GPS signal acquisition in the presence of one, two, and three broadband interferences.

Coarse acquisition false alarm was monitored for the spatial-only beam former, tapped lines space-time beam former, and without beam former cases. Table 1 shows the total number of satellites that are shown to be successfully acquired by the coarse acquisition program. Table 2 shows the number of false alarm among these successfully acquired cases. We did not detect any coarse acquisition false alarm cases for the spatial-only beam former and without beam former cases. For the space-time beam former, a total of 10 false alarm cases were detected among 133 acquisitions that were flagged as successful. This corresponds to 7.5% false alarm rate in the course acquisition procedure.

Table 1. Total number of satellites shown to be successfully acquired during coarse acquisition

ISR (dB)	Space-only	Space-time	No beam
20	51	56	56
30	41	46	28
40	28	31	1

Table 2. Total number of false alarm cases

ISR (dB)	Space-only	Space-time	No beam
20	0	5	0
30	0	3	0
40	0	2	0

2.4.3 Fine acquisition success rate and false alarm rate.

The fine acquisition algorithm generates the fine Doppler frequency and signal to noise ratio, if the procedure is successful. The success of the fine acquisition algorithm is critical to the determination of the navigation data bit transition and carrier and code tracking. The output signal to noise ratio, success rate, and false alarm rate are indicators of the algorithm performance. Table 3 shows the total number of satellites that are shown to be successfully acquired by the fine acquisition program. Table 4 shows the number of false alarm among these successfully acquired cases. Notice again that the false alarms only occurred with the space-time beam former with an average of 7% of false alarm rate.

Table 3. Total number of satellites shown to be successfully acquired during fine acquisition

ISR (dB)	Space-only	Space-time	No beam
20	51	55	56
30	41	44	28
40	26	30	1

Table 4. Total number of false alarm cases

ISR (dB)	Space-only	Space-time	No beam
20	0	5	0
30	0	2	0
40	0	2	0

A through analysis of the fine acquisition output signal to noise ration generated using experimental data is being carried out at the present time.

2.4.4 Beam former output signal to noise and interference ratio.

The antenna array gain pattern provides a qualitative measure of the beam former performance. In order to quantitatively access a beam former performance, other parameters are needed. One of the parameters is the beam former output signal to noise and interference ratio

(SNIR). Because of the low GPS signal power, it is impossible to directly measure the SNIR. An indirect approach has been developed that provides reliable measure of a beam former output SNIR. This approach is based on the fact that there is a unique relationship between the software receiver coarse acquisition gain, the procedure employed in the acquisition algorithm, and the data length used in the acquisition process to obtain the gain. For example, for the flexible coarse acquisition algorithm shown in figure 8, we can calculate the coarse acquisition gain *Gc* as a function of the total data length *n* (in units of ms) used in the acquisition procedure using the following formula:

$$G_c = 20 - 10\log\frac{1+\sqrt{1+0.44n}}{2.2} \tag{1}$$

Figure 13 shows this relationship based on theoretical calculations. This calculation results have also been validated using Monte Carlo simulations.

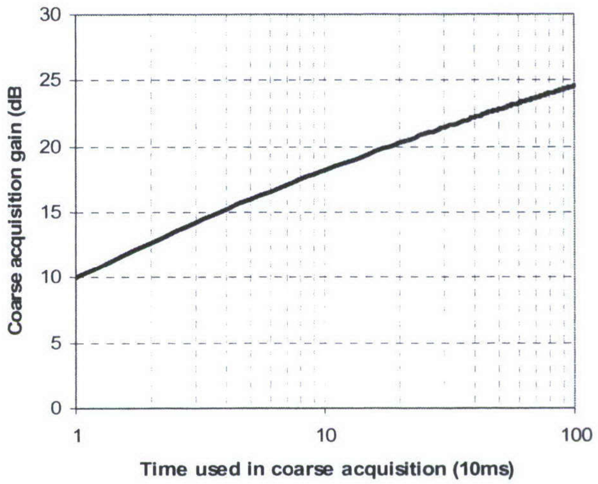


Fig. 13. Coarse acquisition gain as a function of data length used in the processing.

The beam former output SNIR (denoted as SNR_B) can be calculated using the coarse acquisition output signal to noise ratio SNR_C and the coarse acquisition gain G_C:

$$SNR_B = SNR_C - G_c \tag{2}$$

We computed the signal to noise ratio SNR_B for all successfully acquired satellite signals. We performed this procedure for 21 sets of experimental data containing broadband jamming sources using space-only MOP beam forming (number of tap=1) and for space-time MOP beam forming with number of taps equal to 2, 3, and 4 respectively. For each space-time beam forming processor, we used 1, 2, 3, 4, 5, and 6 delay samples between the taps. As a comparison, we also took the output from the four frond end channels and add them without applying weights and the input the signal to the software receiver without a beam former. For all three types of processing, the SNR_B is further converted to the carrier to noise ratio $C/N0_B$. Figure 14 shows the average beam former output $C/N0_B$ for 1, 2, and 3 interference sources respectively. The red, clue, and green lines in the figures represent the average C/N0 at the

output of a spatial-only beam former, the best performing multi-tap space-time beam former (with optimal number of taps and delays), and the receiver frond end (corresponding to the case without beam former) respectively.

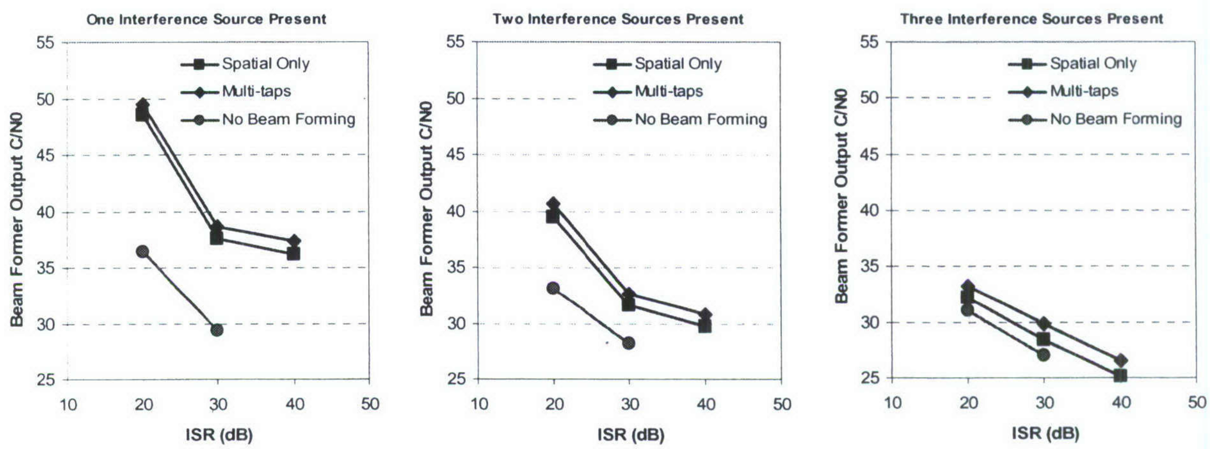


Fig. 14. Average beam former output $C/N0_B$ for successfully acquired GPS signals in the presence of one, two, and three broadband interferences.

We can draw several conclusions from Fig. 14.

(1) Both spatial-only and space-time beam former improves the signal to noise ratio for the software receiver.
(2) The space-time beam former outperforms the space-only beam former by improving the signal to noise ratio by about 1dB on the average.
(3) As the number of interference sources increases, both space-only and space-time beam former performance improvement degrades. When there is one interference source, the beam formers were able to enhance the software receiver signal to noise ratio by an average between 8 to 12 dB. When there are two interference sources, the improvement was reduced to between 4 to 8 dB. When the interference sources number is increased to three, the improvement became 1 to 2 dB.

Fig. 14 should be analyzed along with Fig. 12. Fig. 12 shows the number of satellites that can be successfully acquired through the coarse acquisition procedure. Comparing these two figures, one can see that for the four-channel receiver front end, the beam former performance degrades significantly as the number of interference sources approach the limit set the antenna array's degree of freedom.

2.4.5 Space-time beam former performance analysis.

Theoretical and simulation studies shown that a space-time beam former performance improves as the number of taps increases. Since GPS signals are narrow-band signals, when there are no multi-path input at the receiver (which may well very be the case in this study since the experiment is carried out in an anechoic chamber), the maximum time delay between two

antenna elements is 14 cm. This distance can be translated into a maximum delay time τ_{max} of 0.047 ns. According to Fante and Vacarra (2000), the number of time taps must satisfy:

$$(N-1)T > \tau_{max} \tag{3}$$

where T is the time-tap spacing, or delay time between taps. T must be less than $1/B$, where B is the receiver bandwidth. The receiver front end used in the experiment has a bandwidth of about 4 MHz. Thus the maximum time-tap spacing is T=0.25 μs. From Equation (3), it is obvious that we don't need to have a large number of taps for the GPS receiver. In fact, $N=2$ is more than sufficient for the problem. Using the beam former output signal to interference and noise ratio $C/N0_B$ derived from the last subsection, we quantitatively evaluated the space-time beam former performance for the cases of having 2, 3, and 4 taps. For each tap number used, we tried delay times of 1, 2, 3, 4, 5, and 6 data samples. With a sampling rate of 5 MHz, 1 data sample delay corresponds to 0.2 μs.

Fig. 15 summarizes the average space-time beam former output as a function of number of delay taps for the case of one, two, and three interference sources. One may observe that for all interference sources configurations, increasing the number of taps degrades the beam former performance. It is important to point out here that for reference purposes, we have included the case: number of taps =1. This special case corresponds to the spatial-only beam former. Although we have shown in Fig. 14 that space-time beam former out performs space-only beam former under all conditions, it is important to note that the data points representing the 2, 3, and 4 taps for the space-time beam former are average results, while Fig. 14 shows result for the optimal tap number and delay times. Clearly, Fig. 15 suggests that the space time beam former output signal to noise ratio decreases steadily as the tap numbers are increased, contrarily to previous theoretical and simulation predictions.

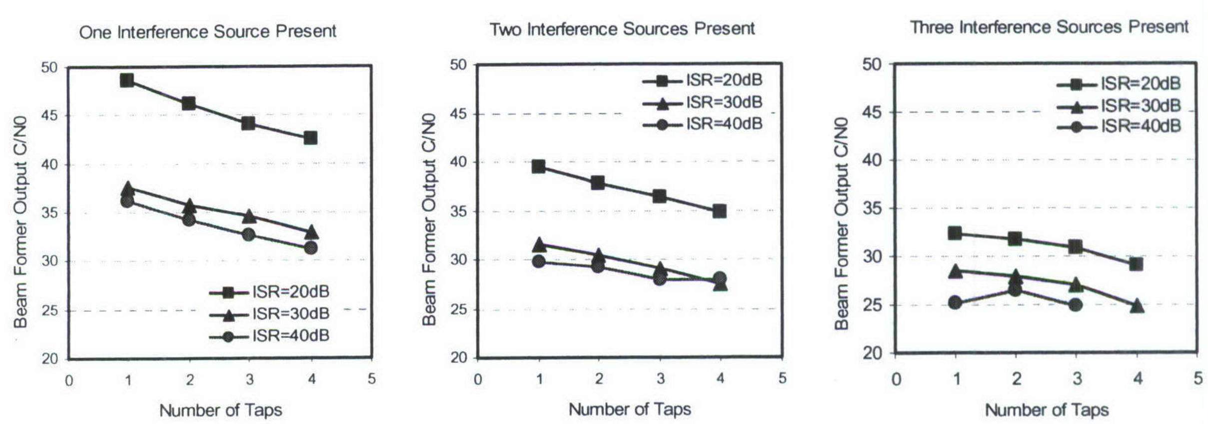


Fig. 15. Average space-time beam former output $C/N0_B$ as a function of number of delay taps for successfully acquired GPS signals in the presence of one, two, and three broadband interferences.

We also studied how the time-tap spacing or delay time between taps impact the beam former performance. Fig. 16 plots the average beam former output signal to noise ratio as a function of delay time between taps. Notice that we used 1, 2, 3, 4, 5, and 6 samples as the delay times. These numbers are chosen based on the following analysis. The receiver front end analog to digital converter has a sampling frequency of 5 MHz, leading to an inter-sample space of 0.2

μs. Since the delay time has to be less than 0.25 μs for our receiver, we are only left with the choice of having one sample as the delay time between two adjacent taps. To test weather the theory really worked, we used the additional 2, 3, 4, and 5 samples as the delay time. The figure clearly shows that the optimum delay time is 4 samples. Also, note that for the delay times used, the difference in the beam former SNR_B can be as high as 10 dB. It is worth mentioning here that the optimum delay time of 4 samples is not simply an average behavior. For each tap number used in the computation and for each data set, the delay time of 4 samples appears to be always the optimal choice.

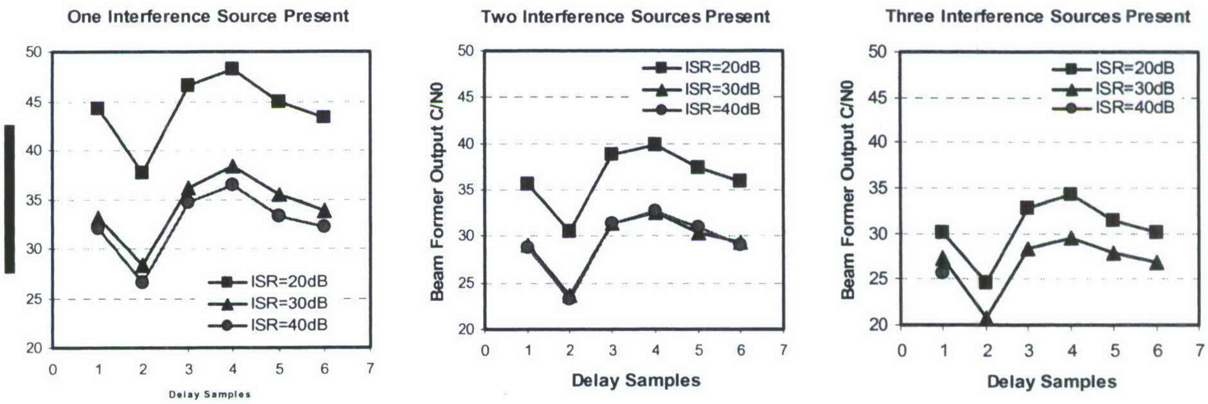


Fig. 16. Average space-time beam former output $C/N0_B$ for successfully acquired GPS signals as a function of delay time between taps.

The above evaluations are all performed using real data. Space only and space-time MOP beam formers are used in the studies. We also implemented the SCORE space only beam former. The antenna array gain pattern for the SCORE beam former did not reveal any desirable pattern. Coarse acquisition algorithms could not generate any consistent successful satellite acquisition from the beam former outputs. The beam forming algorithm has been tested with simulation inputs (without a jammer present) using 4-element and 9-element antenna arrays. Our studies shown that the poor performance of the SCORE algorithm in the experimental data processing is due to an inadequate number of degrees of freedom. The SCORE algorithm is a blind adaptive algorithm. It attempts to obtain an optimal gain pattern for all satellites contained in the input signal. The experimental setup includes 8 GPS satellites while the 4-element antenna array only has 3 degrees of freedom. As a result, the algorithm failed to produce desirable results. Simulations using 9-element antenna array were able to generate satisfactory gain patterns. Figure 17a and 17b shows the gain pattern for a 4-element antenna array and a 9-element antenna array. Simulated GPS signals containing 3 satellites are used to generate the pattern. No jamming signals are included in the simulation. In our next stage of research, jammer sources will be added to the simulation input data.

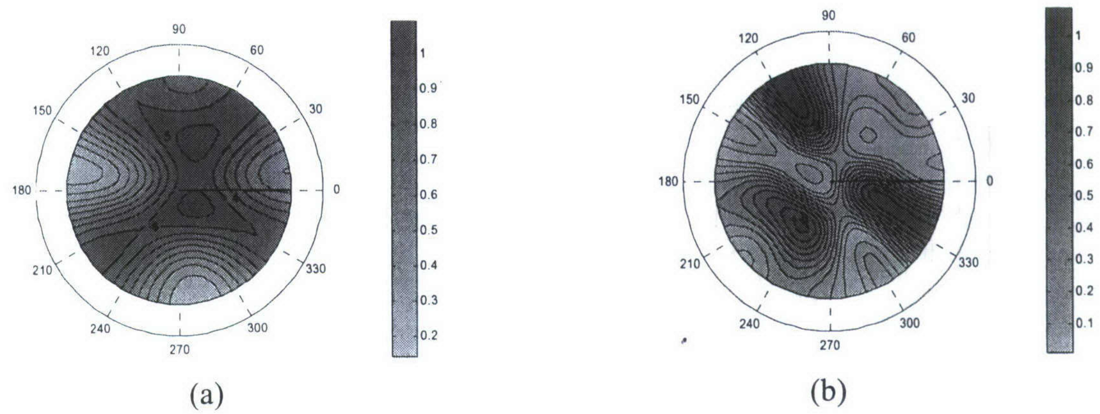


Fig. 17. Simulated antenna array gain pattern for a 4-element (a) and a 9-element (b) front end. Three GPS signals are included in the input simulation data.

2.5. Research Team Status.

The research team consists of the following personnel:

- Dr. Jade Morton, PI, faculty, Miami Unviersity.
- Dr. Qihou Zhou, co-PI, faculty, Miami University.
- Jason Smith, graduate assistant, Miami University.
- Marchus French, graduate assistant, Miami University.
- Gerard Brilleaux, undergrdaute assistant, Miami University.
- Mathew Cosgrove, undergraduate assistant, Miami University.
- Justin Lee, undergraduate assistant, MIT.
- Dr. Lihyeh Liou, SNDI.
- Mr. David Lin, SNRP.
- Dr. James Tsui, independent consultant.

External collaborator for the research team is Dr. Roberta Rojas, Ohio State University.

3. Accomplishments

The research project started in December 2004. We have achieved the following accomplishments in the past ***8*** month time period:

- Established a framework for testing, evaluation, and development of integrated aperture, receiver, and digital beam forming systems.
- Developed algorithms to generate simulated GPS signals for antenna arrays composed of isotropic antenna elements.
- Worked with experimental data containing GPS signals in controlled jamming environment collected by a conventional 2x2 antenna array and 4 channel radio frequency front end.

- Implemented three beam forming processors including a constraint minimum output power (MOP) spatial processor, a constraint MOP space-time processor, and a blind adaptive processor based on GPS signals self-coherence properties.
- Developed visualization techniques for antenna gain pattern studies.
- Applied software GPS receiver coarse acquisition and fine acquisition algorithms to work with digital beam former outputs generated using both simulation and real experimental data.
- Developed criteria and measures for the receiver and beam former performance evaluations, applied the criteria and measures to the real data and simulation, and has obtained several important qualitative and quantitative evaluations of the beam formers developed and current software receiver.
- Met with Dr. Roberta Rojas from Ohio State University and developed preliminary plans for collaboration using reconfigurable antennas for the receiver front end. Dr. Rojas provided reconfigurable antenna gain and frequency response simulation data in late July 2005.
- A paper has been submitted to and accepted by the Institute of Navigation Global Navigation Satellite Systems (ION GNSS) conference. The paper will be presented on Sept 15, 2005 in Long Beach, CA. Several presentations have been made on related subjects.
- A journal paper is currently under preparation for publication.

4. Personnel Supported

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5. Technical Publications

Morton, Y. T. J., L. L. Liou, D. M. Lin, J. B. Tsui, and Q. Zhou, "Broadband interference cancellation using digital beam forming and a software receiver," *Proc. 2005 ION GNSS Conference*, Sept. 13-17, 2005, Long Beach, CA.

6. Interactions/Transitions

[1] Presentations

Morton, Y. T., "Software GPS Receivers and Digital Beam Forming," ECE Distinguished Speaker Seminar Series, Illinois Institute of Technology, Dec. 4, 2005, Chicago, IL.

Morton, Y. T., Q. Zhou, "Research in Software GPS Receivers and Applications at Miami," Join Miami ECE Departmental Symposium and ION Dayton Section Seminar, May 11, 2005, Oxford, OH.

Morton, Y. T., "Integrating Beam Forming and A Software GPS Receiver," 2005 IEEE MTT IMS Software Radio Workshop, June 17, 2005, Long Beach, CA.

Morton, Y. T., "Software GPS Receiver and Applications," Invited Presentation, Department of Electronic Science and Engineering, Nanjing University, June 30, 2005.

Morton, Y. T., "An integrated test bed and research platform for reconfigurable antenna, digital beam forming, and software receiver," Ohio State University, July 15, 2005.

Morton, Y. T. J., L. L. Liou, D. M. Lin, J. B. Tsui, and Q. Zhou, "Broadband interference cancellation using digital beam forming and a software receiver," to be presented at the 2005 ION GNSS Conference, Sept. 13-17, 2005, Long Beach, CA.

[2] Transitions

The following list of people has been provided with the software algorithm, documentations, or hardware developed under this contract:

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Sun, W. and M. Aimin, "A self-coherence based GPS Anti-jamming receiver," Submitted to *IEEE Trans. Signal Processing*, 2003.

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Zoltowski, M. D. and A. S. Gecan, "Advanced adaptive null steering concepts for GPS," *Proceedings of the 1995 Millitary Communications Conference*, vol.3, P1214-1218, 1995.